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THE SPECTRUM OF THE BROWN DWARF CANDIDATE PC0025+0447

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ABSTRACT

A spectrum of the cool dwarf star PC0025+0447 obtained with the Low Resolution Imaging Spectrograph at the Keck telescope yields an upper limit on the lithium to hydrogen ratio. The limit is temperature dependent and ranges from 5×10^{-10} for an effective temperature of 2500 K to 1×10^{-10} at 1900 K. A definitive spectrum of the star's chromospheric emission is presented, but the prominence of the Balmer series is due to the weak thermal emission of the photosphere, rather than extraordinary activity. PC0025+0447 seems more likely to be a cool main sequence star than a young brown dwarf.

1. INTRODUCTION

The discovery by Schneider *et al.* (1991) of an M star with outstandingly strong Hα has naturally led to speculation that PC0025+0047 and other stars appearing to form an extension of the main sequence are young stars which will eventually fail to stabilize on the main sequence and become brown dwarfs. Infrared spectrophotometry of PC0025+0047 by Graham *et al.* (1992) shows a strong water vapor absorption spectrum, and comparison with models has suggested an effective temperature of 1900±600 K. Tinney *et al.* (1993) obtained a distance of 71±15 pc from a photometric parallax which assumes the star is located on the main sequence in a $(K,I-K)$ color magnitude diagram. Optical spectroscopy at a resolution higher than the 25 Å of the discovery paper has been held back by low flux in the visible region ($AB_\nu>24$ mag). The Keck telescope has provided the answer to that problem.

2. OBSERVATIONS

The Low Resolution Imaging Spectrograph for the Keck 10 m telescope is described in Oke *et al.* (1994). The detector is a 2048×2048 Tektronix CCD; readout occurs using two of the four amplifiers. The spectrum of PC0025+0047 is a 3000 s exposure taken on 1993 Oct. 22 with the 300 g/mm grating set at 6300 Å using a 1.0 arcsec slit. This gives 2.3 Å/pixel, with a scale of 4.6 pixels/arcsec. The spectrum covers the range from 3805 to 8870 Å in a single exposure. No order blocking filter was used, as the object is so red that it was not necessary. The seeing was approximately 1.5 arcsec. We should have used the 1.5 arcsec slit, given the seeing, but that was cannibalized to provide room for a 4 arcsec slit with which to observe standard stars. PC0025+0447 was easily visible on the slit-viewing TV guider. There were some minor guiding problems during the exposure, and some light was lost due to them.

The data were processed in a standard manner using FIGARO. The peculiarities introduced by the two amplifier CCD readout used by the LRIS electronics were suitably taken into account. Figure 1 shows the resulting sky subtracted spectrum. Atmospheric absorption bands have not been removed. The wavelength calibration was provided by a spectrum of an argon and a mercury lamp taken immediately after the exposure of the brown dwarf candidate. Note the strong emission lines in the Balmer series with emission extending to at least H8, while there is no sign of emission from H and K of Ca II. Considering that the existing LRIS camera was designed as the red side of a double spectrograph, it is remarkable that lines as blue as H8 at 3835 Å can be seen. Figure 2 shows the red half of the spectrum; Hα is off scale here so that the molecular features can be seen.

The strengths of the emission lines are given in Table 1. They are probably somewhat underestimated due to minor guider problems, small slit losses, etc. The fluxes were derived from observations taken later that same night through a 4 arcsec slit of the standard star G191B2B whose energy distribution is given by Oke (1990). Although this star was observed only without a blocking filter, the standard HZ4 was observed with the same setup both with and without an order blocking filter on the previous night. Both of these stars are DA white dwarfs. The correction for second order contamination by blue light in the red part of the spectrum for the standard star is under 10%, and is ignored.

The values in Table 1 are in reasonable agreement with those reported for Hα and Hβ by Schneider *et al.* (1991). The same flux calibration, however, shows poor consistency with the photometry of Schneider *et al.* (1993). By integrating over the R (Cousins) bandpass, we are able to recover the red magnitude of the standard star, but we obtain $R=22.35$ for PC0025+0447. After transformation to the 4Shooter system, by referring to photometry by Bessell (1992) and Kent (1984), we have $r_4=22.8$, compared with $r_4=22.1$ from Schneider *et al.* (1993). We cannot be sure whether line or continuum variations or slit losses are the source of these differences. We retain raw scales for Figs. 1–3 to acknowledge our calibration uncertainties.

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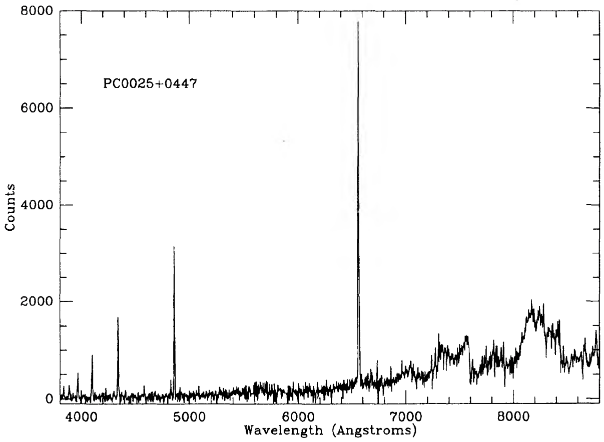

FIG. 1. The spectrum of PC0025+0447 over the full range covered by the LRIS.

Higher resolution observations of the Hα line with the double spectrograph on the Hale 5 m (Reid *et al.* 1994) give $V_{rad}=-2\pm15$ km s^{-1}. The LRIS spectra support this value, but uncertainties in flexure corrections do not allow us to improve on this value.

3. NONDETECTION OF LITHIUM

Boesgaard & Steigman (1985) have reviewed the evidence for an initial lithium to hydrogen ratio in young stars of 1×10^{-9}. Lithium is depleted in low mass stars by the combined action of convection and nuclear reactions. Stars at the end of the main sequence are fully convective. Although the lithium depletion time scale for the lowest masses has not been calculated, the order of magnitude e-folding time for solar type stars is 1 Gyr. If the mass of PC0025+0447 is less than $0.06\mathscr{M}_\odot$, its age is less than 1 Gyr (Graham *et al.* 1992), and lithium may be present in the atmosphere at close to its original abundance.

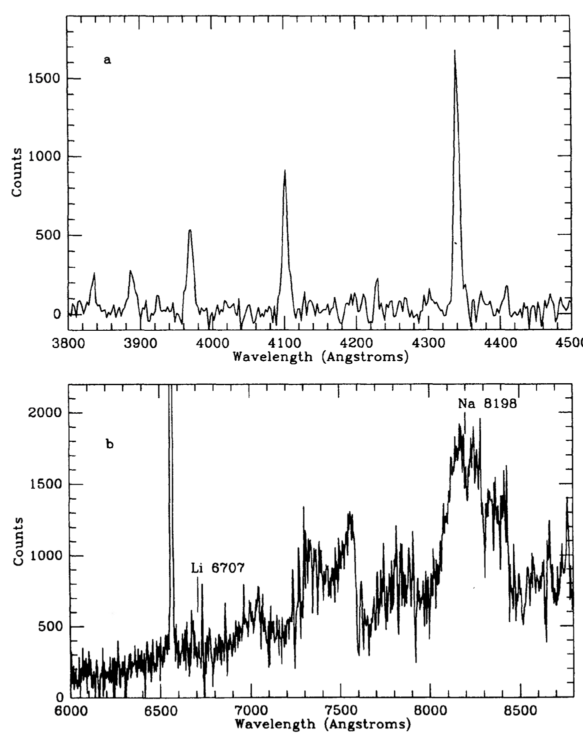

FIG. 2. (a) The wavelength range 3800–4500 Å showing the Balmer series in emission from Hγ through H9. (b) The wavelength range 6000–8850 Å. Note that the peak of the Hα emission is far off scale. Strong molecular bands of TiO at 7054 and 7589 Å and of VO are present.

TABLE 1. Emission line strengths.

λ (Å)	Flux (10^{-16} erg s^{-1} cm^{-2})	% Error
6562	4.6	±3%
4861	2.0	±6%
4340	1.7	±7%
4101	1.2	±10%
3970	1.0	±13%
3889	0.69	±18%
3835	0.48	±25%

Note that slit losses discussed in Sec. 2 are not included in the uncertainties estimated above.

The upper limit on the equivalent width of the Li I doublet at 6707 Å in the spectrum in Fig. 2 is 1.4 Å. Since lithium has a similar ionization potential to sodium, and since neither atom is significantly depleted by molecular association for $T>1680$ K, it is useful to compare the line strength with that of the Na I doublet at 8190 Å, which has an equivalent width in the range 2.5 to 5.7 Å. The large uncertainty in this measurement is due to an apparent blend with a longer wavelength unidentified (presumably molecular) feature at 8206 Å.

Our calculation of the weak line strength ratio is given in Fig. 3. This calculation takes into account partial ionization

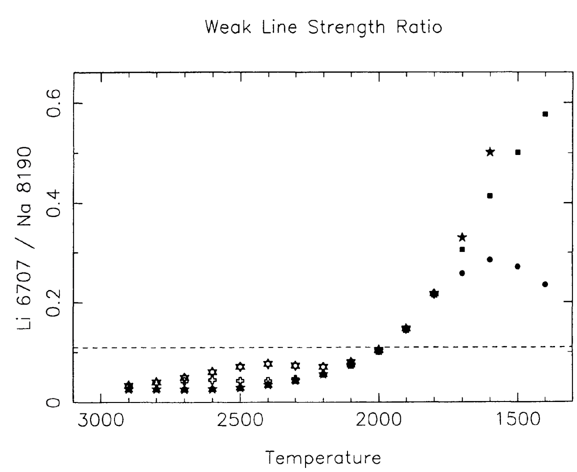

FIG. 3. The predicted strength of lithium compared with sodium as a function of temperature. The calculation is for weak lines and is based on the ratios of line and continuous opacities for Li/H=3×10^{-10} and Na/H=2×10^{-6}. The observed upper limit is given by the dashed line. Different symbols refer to choice of gas pressure and electron pressure. Solid symbols: $P_e=10^{11}$, open crosses: $P_e=10^{10}$, open stars: $P_e=10^9$. Solid stars: $P_g=10^4$, solid squares: $P_g=10^5$, solid circles: $P_g=10^6$.

TABLE 2. Upper limits on Li/H.

T_{eff}	T_{ex}	Li/H$\times10^{10}$
2500	2100	5
2300	1950	2
1900	1600	1
1550	1300	1

of both elements, the 2.1 eV excitation of the lower level of sodium, and assumes the continuous opacity is given at both 6707 and 8190 Å by the mean values tabulated by Collins & Fay (1974). Oscillator strengths for these lines are from Kurucz & Peytremann (1974). The Li/H abundance ratio is 3×10^{-10} and the Na/H ratio is 2×10^{-6} in Fig. 3.

The upper limit on the observed ratio of λ6707/λ8190 of 1/3 corresponds to an upper limit of 1/9 in weak line strength, assuming both lines lie on the square root part of the curve of growth. This limit is indicated by the dashed line in Fig. 3.

A range of possible physical conditions is considered for the line forming region: electron densities from 10^9 to 10^{11} cm^{-3} and gas pressures, P_g, from 10^4 to 10^6 dyn cm^{-2}. Depletion of lithium by molecule formation is taken from Tsuji (1972).

We conclude from Fig. 3 that for the range of likely temperatures in the line forming region of the atmosphere of PC0025+0447, the lithium to hydrogen ratio is less than 1×10^{-9}. Table 2 provides more explicit upper limits for different values of the stellar effective temperature (T_{eff}) and the temperature in the line forming region (T_{ex}), assumed to be $0.84T_{eff}$ according to a gray model temperature/optical depth relation. We have assumed $\log P_g<5.5$ in deriving these limits.

A stronger upper limit would likely be set by spectrum synthesis, as our assumption about the continuous opacity has greatly depressed the predicted Li/Na line ratio, and mean opacities are known to underestimate the continuum flux (Carbon 1974) in radiative transfer calculations.

4. THE EMISSION SPECTRUM

PC0025+0447 originally drew attention to itself through the strength of the Hα emission. Balmer emission is relatively common amongst M dwarfs, although no others approach PC0025+0447 in strength, and are tied to chromospheric activity (Cram & Mullan, 1979). Joy & Abt (1974) originally demonstrated that the fraction of dMe stars increases with decreasing mass, with all stars M5 and later in their sample having Hα in emission. However, subsequent spectroscopic surveys (Liebert *et al.* 1979; Giampapa & Liebert 1986) have shown that there are late-type M dwarfs with no detectable emission. Given that the magnetic dynamo powering the chromospheric activity is expected to decline with time, Giampapa and Liebert proposed age as the dominant factor in determining Hα emission flux. The decrease in activity from the Pleiades ($\sim7\times10^7$ yr) to the Hyades ($\sim7\times10^8$ yr) to the field (few Gyr on average) supports this hypothesis to some extent, although there is a clear range in activity at any given luminosity (Prosser *et al.* 1991), suggesting that the emission is moderated by another process (rotation?). In any event, the prominent Balmer lines in PC0025+0447 have prompted suggestions that the star is extremely young—possibly even a brown dwarf.

TABLE 3. Line ratios.

Line	PC0025	Bond Q	Gl 65B Q	Gl 65B F	Gl 388 Q	Gl 388 F	PN
Hα	2.3	1.35					2.7
Hβ	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hγ	0.85	0.75	0.43	0.5	0.5	0.80	0.47
Hδ	0.60	0.50	0.28	0.34	0.28	0.70	0.26
Hϵ	0.50	(0.35)					0.16
Hζ	0.35		0.22	0.24	0.20	0.50	0.11
H9	0.24		0.16	0.21	0.12	0.40	0.08
Ca II K	<0.02	1.2	0.5	0.42	0.6	0.13	

Balmer decrement measurements (relative to Hβ) for PC0025 and for three other dMe stars—Bond's flare star (Greenstein 1977), Gl 65B (UV Ceti; Phillips *et al.* 1988) and Gl 388 (AD Leo, Hawley & Pettersen 1991). The latter two stars have measurements both during quiescence (Q) and while a flare was in progress (F). The final column lists Case B recombination values for T=20 000 K (Pengelly 1964).

Table 3 compares the line ratios measured from our spectra with observations of other dMe stars—Gliese 388 (AD Leo, $M_v=10.95$; Petterson & Hawley 1991); Gliese 65B (UV Ceti, $M_v=15.6$; Phillips *et al.* 1988); and Bond's star ($M_v=13.0$; Greenstein 1977). All three are flare stars, and Table 3 lists data for Gl 388 and Gl 65B both during an outburst and in quiescence. One clear difference between these stars and PC0025 is the absence of Ca II emission in the latter. This makes comparisons with chromosphere models difficult, since most calculations have concentrated on either the H & K lines or the Ca II/Hα ratio (Robinson *et al.* 1990). Cram & Mullan (1979) have computed Balmer line ratios for a number of chromosphere models, but most of their calculations are tied to a 3500 K photosphere. Converting the predicted equivalent width to fluxes, their model 7—which has the steepest temperature gradient in the lower chromosphere—gives the closest match to the PC0025 observations (Hα/Hβ/Hγ=2.4/1.0/0.9). However, their models predict a central reversal, $\sim$1.5 Å wide, in the emission line profile. While this reversal may not be detectable in the Keck data (2.4 Å pix^{-1}), we have higher resolution spectra of the Hα region ($\sim$0.7 Å pix^{-1} from the double spectrograph on the Palomar Hale 5 m) which are single-peaked.

The upper limit listed in Table 3 for Ca II K corresponds to a line intensity 10% that of the H9 line. In the other dMe stars, the Ca II lines (H blends with Hϵ) are at least as strong as Hδ, or a factor of twenty to thirty stronger than our limit. Obviously, PC0025+0447 is substantially fainter (and cooler) than the three comparison stars. There are few spectroscopic observations covering the H & K regions of other very low mass (VLM) stars, but these observations reveal no anomalies in Ca II. Gliese 406 (Wolf 359, $T_{eff}\sim2550$ K, $M_{bol}=12.1$) was observed both during an outburst and in quiescence by Greenstein & Arp (1969), and in both cases the K line is at least as strong as Hδ. Herbig (1956) caught VB 10 ($T_{eff}\sim2400$ K, $M_{bol}=12.9$) during a flare, and his spectrum shows prominent Ca II emission. Normally this star has only low-level emission at Hα ($\sim$4 Å equivalent width), and we are not aware of any observations during quiescence of the higher Balmer lines or H & K.

With the absence of Ca II, one might speculate whether the emission could be due to a chance alignment with an ionized gas cloud. However, our spectra show no evidence that the emission lines are spatially extended beyond the seeing disk. Moreover, we have also listed in Table 3 the Balmer decrement predicted for Case B recombination in a 20 000 K plasma that is optically thick at Ly α (Pengelly 1964). The gaseous spectrum declines at a substantially steeper rate towards higher order lines than the PC0025+0447 data, which have a Balmer decrement closer to the chromospheric observations. Indeed, the relative intensities of $H\zeta$ and H9 lie between the observations of AD Leo and UV Ceti at outburst, implying high temperatures in the chromosphere. The total flux emitted in the Balmer lines is $\sim 1.2\times 10^{-15}$ erg s^{-1} cm^{-2}, or nearly 0.1% of the bolometric luminosity (1.5×10^{-12} erg s^{-1} cm^{-2}; Schneider *et al.* 1991). This is close to Greenstein's (1977) estimate of the fractional luminosity of the quiescent chromosphere in Bond's flare star.

A useful comparison sample of faint dwarfs is provided by the Hyades (Reid & Hawley 1994). For the Hyades, the mean value of the ratio of $H\alpha$ flux to bolometric flux is $R=1\times 10^{-4}$ with a lognormal dispersion of 0.3 dex. There is no trend with stellar luminosity. The same ratio for PC0025+0447 is $R=3\times 10^{-4}$. A second sample of the faintest stars is that of Schneider *et al.*, for which $\langle R\rangle = 4\times 10^{-5}$. We conclude that while the equivalent width of $H\alpha$ in PC0025+0447 may be exceptionally large, the flux of $H\alpha$ is not extraordinary for a star of the age of the Hyades.

5. CONCLUSIONS

A strong candidate for a brown dwarf might be (1) significantly younger than 10^9 yr, (2) significantly cooler than 2500 K, (3) significantly less massive than $0.1\mathscr{M}_\odot$, (4) undepleted in lithium at $Li/H=10^{-9}$, or some or all of the above. PC0025+0447 is not a *strong* candidate by any of these criteria.

(1) The Hyades (age 0.7 Gyr) seem to be a satisfactory match to PC0025+0447 in chromospheric activity.

(2) The effective temperature is uncertain, but could be as high as 2500 K.

(3) The mass is unknown.

(4) If the temperature is 1900 K or below, and if the sodium abundance of the star is close to solar, lithium is significantly depleted.

An approximate age of 1 Gyr and a location at the end of the main sequence remains a viable hypothesis for PC0025 +0447. To pursue the tantalizing possibility that it *is* a brown dwarf after all, the most rewarding approaches will be (theory) detailed spectrum synthesis including some polyatomic molecules, and (observation) a trigonometric parallax for the star.

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